Int. Workshop on EUV and Soft X-Ray Sources
November 7-9, 2016, Amsterdam / NL

Applications of a Table-top Laser Driven EUV/Soft X-ray Source and Wavefront Optimization at Short Wavelengths

Klaus Mann

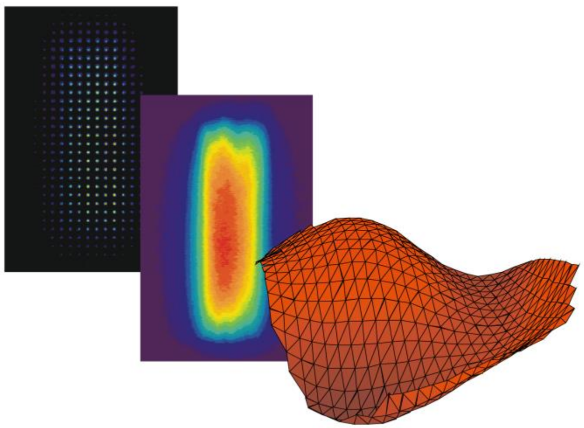
J.O. Dette, J. Holburg, U. Leinhos, M. Lübbecke,
T. Mey, M. Müller, M. Schellhorn, M. Stubenvoll, B. Schäfer

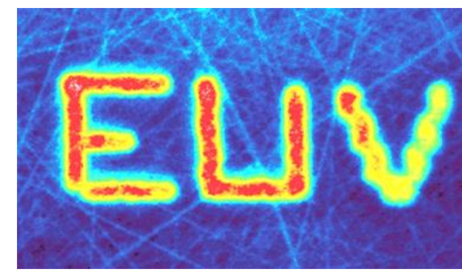
Laser-Laboratorium Göttingen e.V.
Hans-Adolf-Krebs Weg 1
D-37077 Göttingen

Dept.
“Optics / Short Wavelengths”

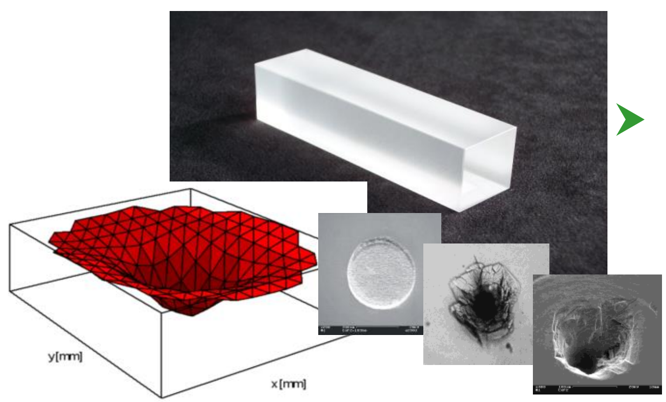
Laser-
Laboratorium
Göttingen e.V.

- **Optics test** (NIR…**193 nm**)
  - *(Long term) degradation (10^9 pulses)*
  - *Non-linear processes*
  - *LIDT*
  - ***Absorption** / Scatter losses*
  - *Wavefront deformation*



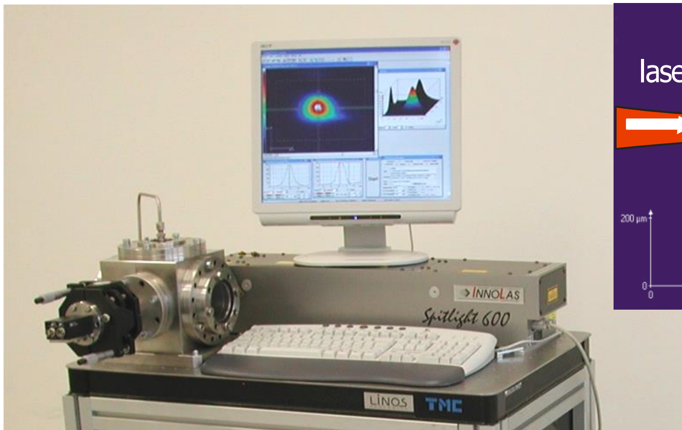


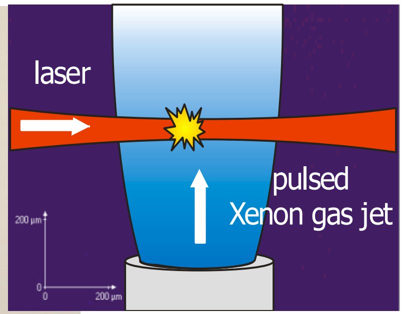
- **Beam propagation**
  - *Wavefront*
  - *Spatial coherence*
  - *M^2*

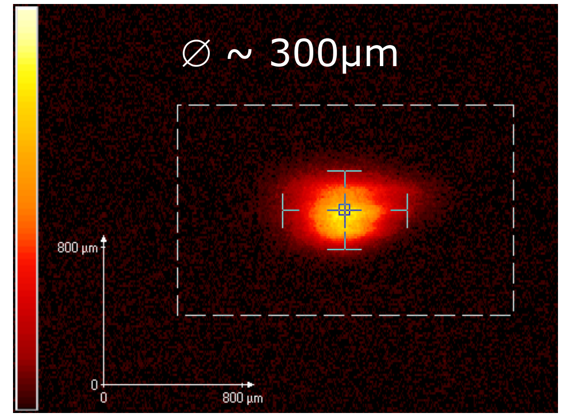


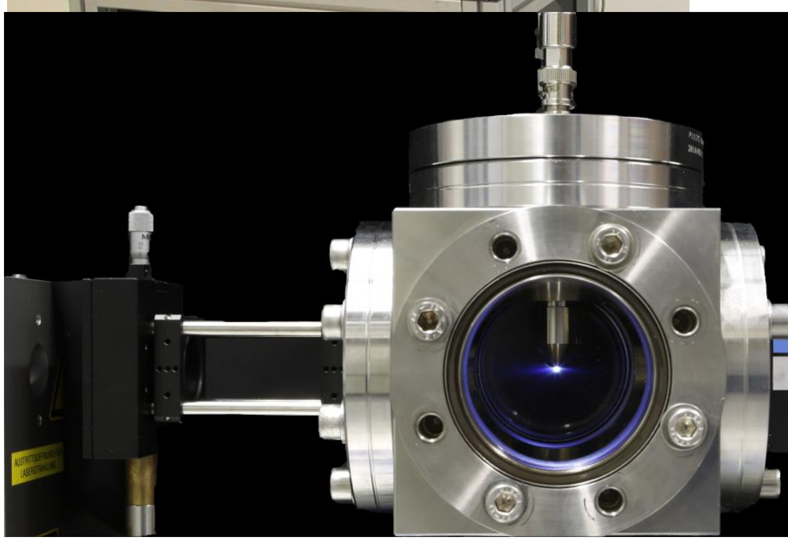
- **EUV / soft x-ray source**
  - *Metrology*
  - *Absorption Spectroscopy*
  - *Microscopy (“water window”)*
  - *Material interaction*

Laser plasma source for extreme UV and soft x-ray radiation









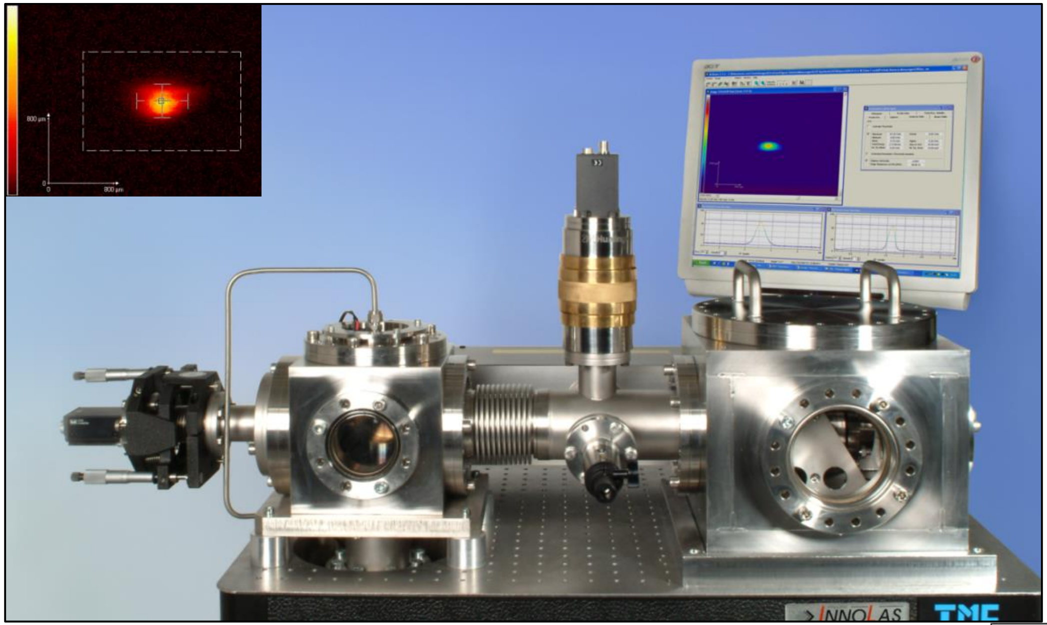
- Compact
- Continuous supply of target material
- Low debris generation
- Long-term stability

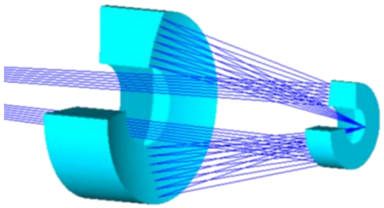
→ various applications…

S. Kranzusch, K. Mann, Optics Comm. **200**, 223 (2001)

Schwarzschild optics

→ EUV direct structuring

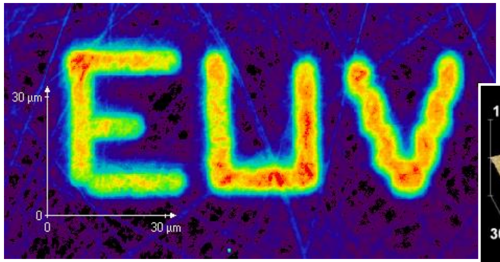




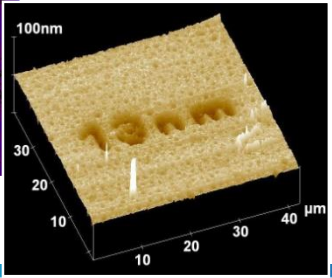
- Imaging of plasma (10x)

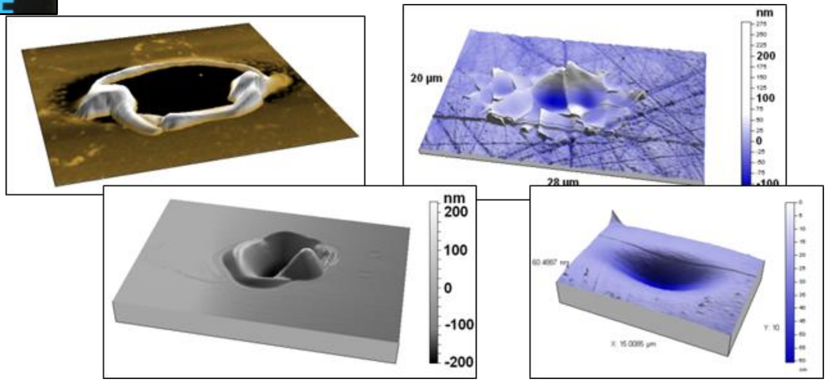
⇒ Micro-focus with
  high EUV fluence @ 13.5 nm

- Ablation studies
- Damage testing of EUV optics



PMMA



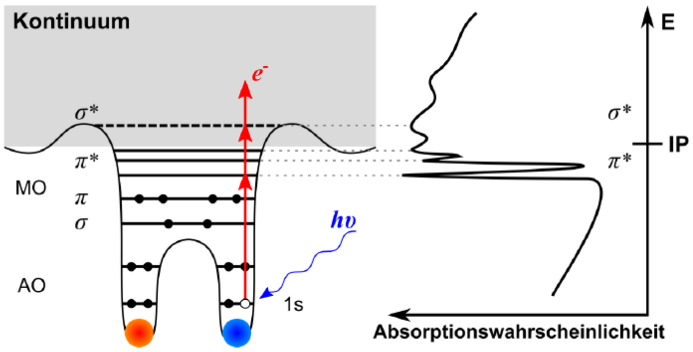


F. Barkusky, K. Mann: Appl. Phys. A 105, 17 (2011)
F. Barkusky, K. Mann et al., Optics Express 18, 4347 (2010)

Soft x-rays : Absorption Spectroscopy

Laser-Laboratorium Göttingen e.V.

NEXAFS = Near-edge x-ray absorption fine-structure



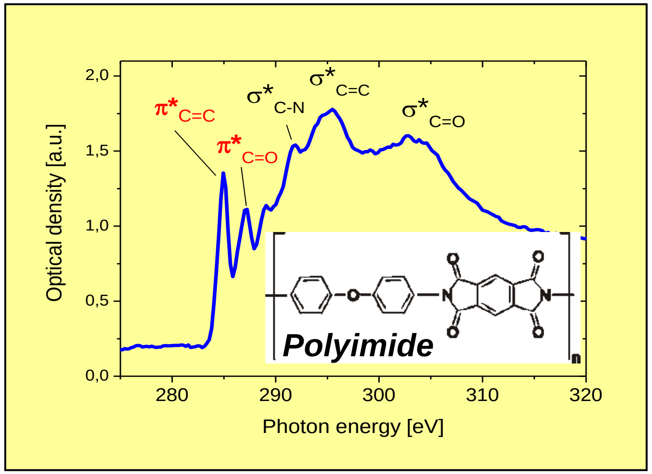
- Excitation into unoccupied molecular orbitals
  → „Fingerprint“ of molecules

- surface-sensitive chemical analytics
- polychromatic concept („single-shot“)
- transmission of thin samples

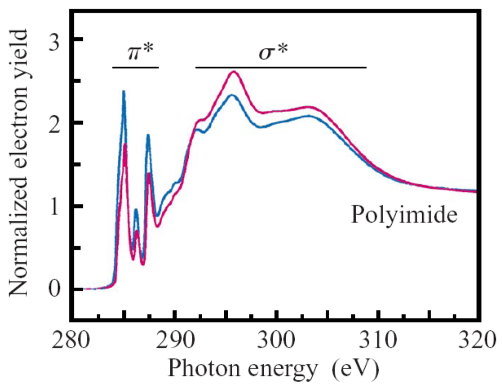
- Kr Plasma → „water window“
- Polyimide at Carbon K-edge, 60 pulses:

C. Peth, K. Mann et al.,

J. Phys. D **41** (2008) 105202

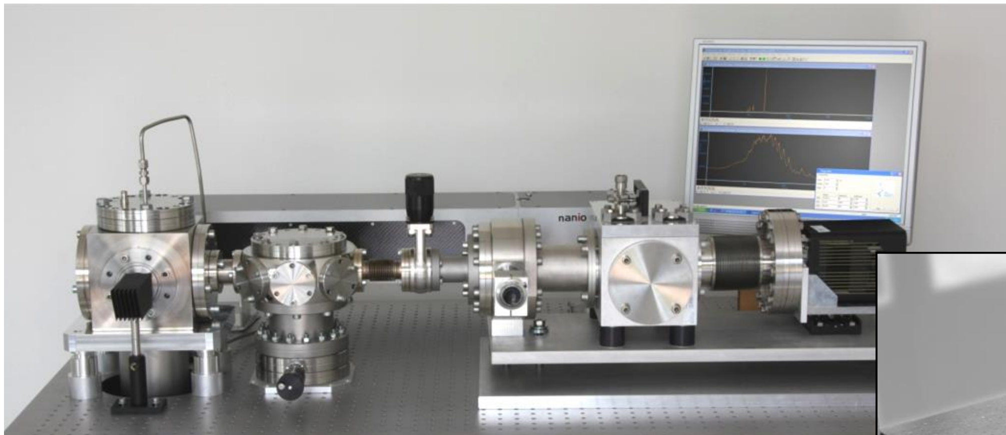


Synchrotron data (J. Stöhr):



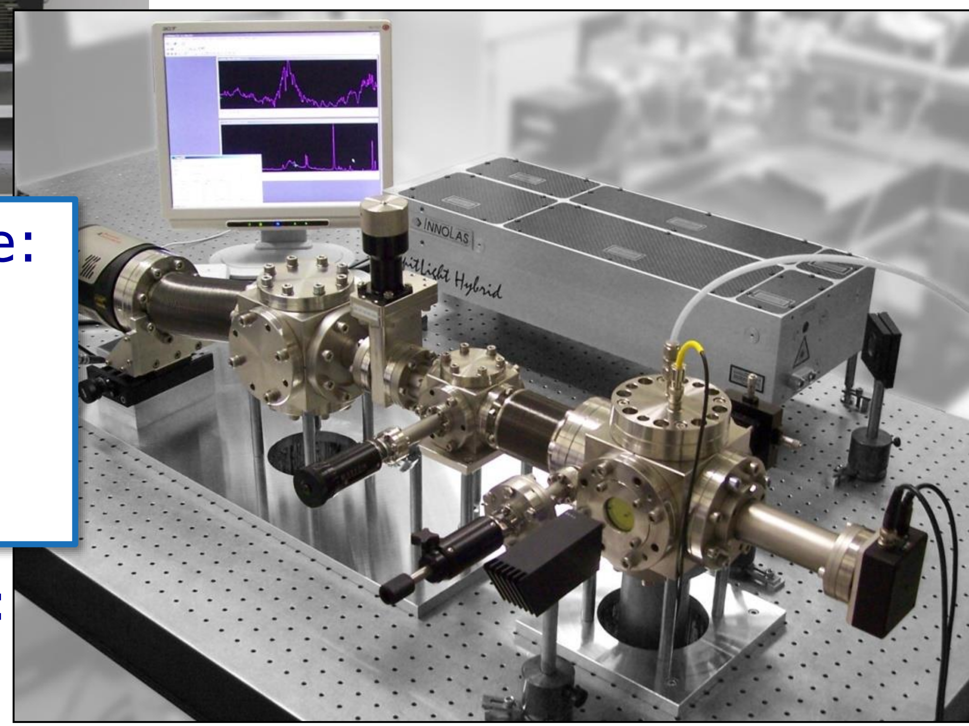
Two NEXAFS Spectrometers:

Laser-
Laboratorium
Göttingen e.V.



◄ XUV – NEXAFS (1 - 5 nm)

▼ EUV – NEXAFS (7 - 20 nm)



Fine-structure of absorption edge:

- molecular orbitals
- oxidation states
- coordination of absorbing elements

- Accessible x-ray absorption edges: C, N, O, Cl, S, Ca, Mn, Fe, Cu, Ti, Pr…

Mn L-edge, Fe L-edge

Different Mn compounds

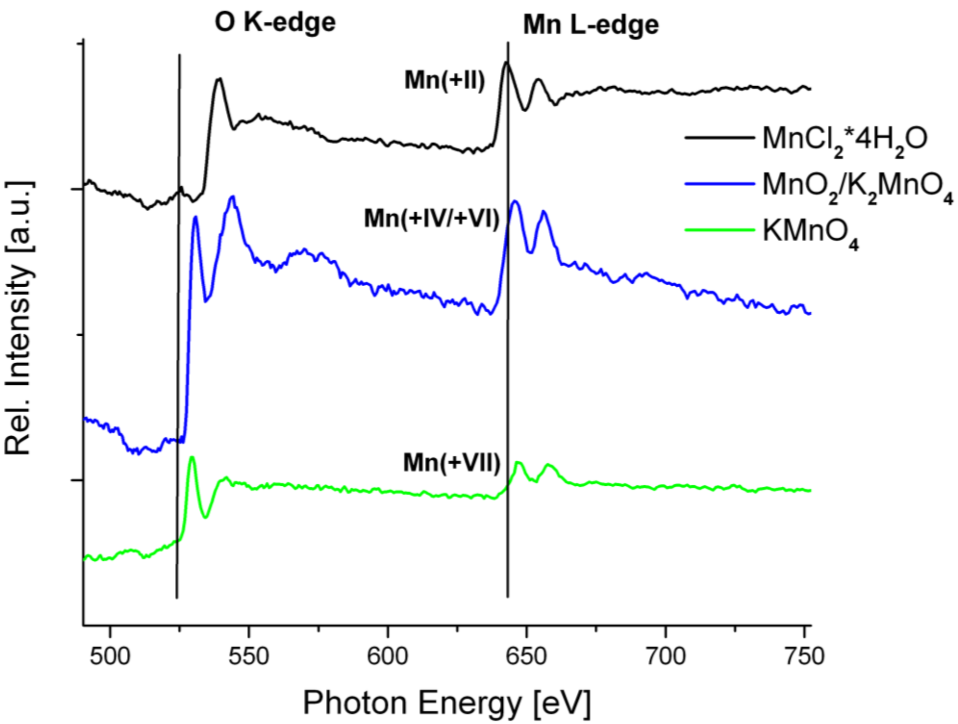
➢ Different oxidation states of Mn

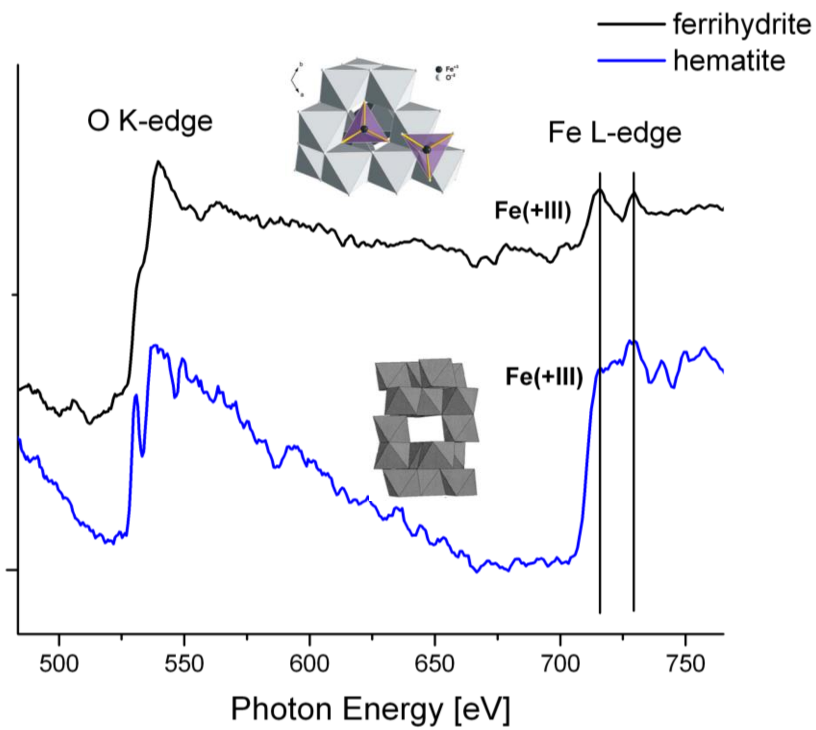
→ Chemical shift

Different iron minerals

➢ both tri-valent

➢ but different coordination

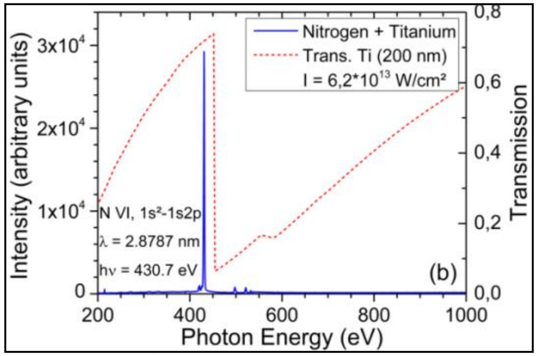




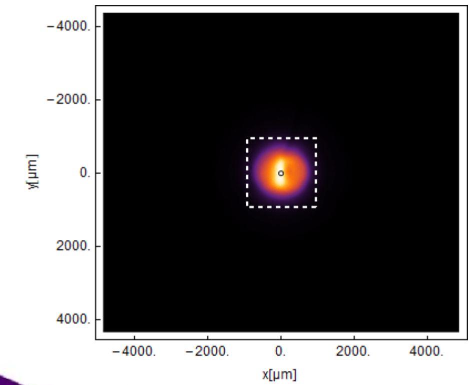
M. Schellhorn, J. Niemeyer, Univ. Göttingen

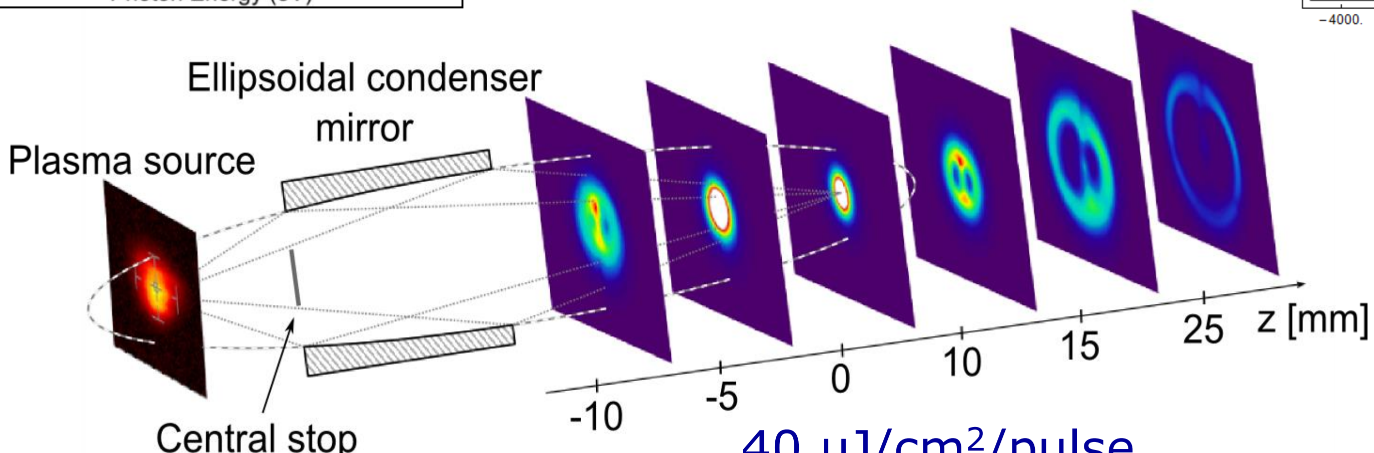
Focused monochromatic radiation @λ=2.88nm

→ Soft x-ray microscope



Ti-filtered spectrum of N_2 plasma @λ=2.88nm



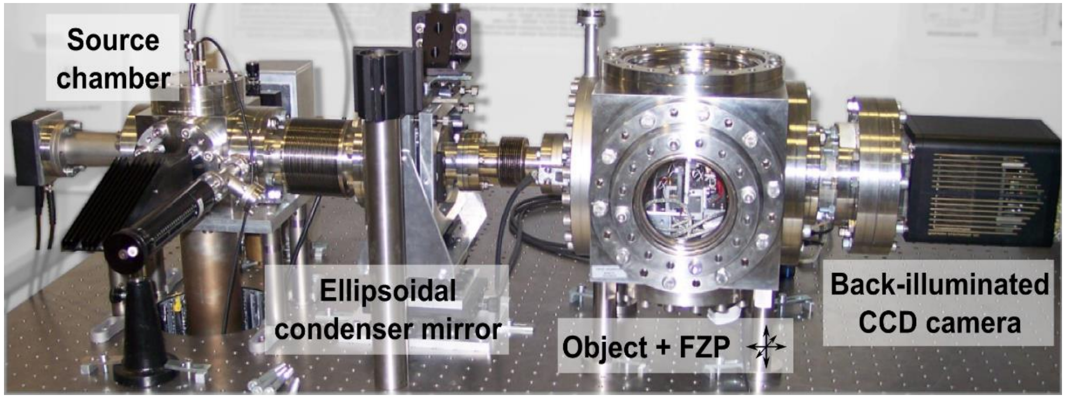


Intensity profiles captured by phosphor coated CCD

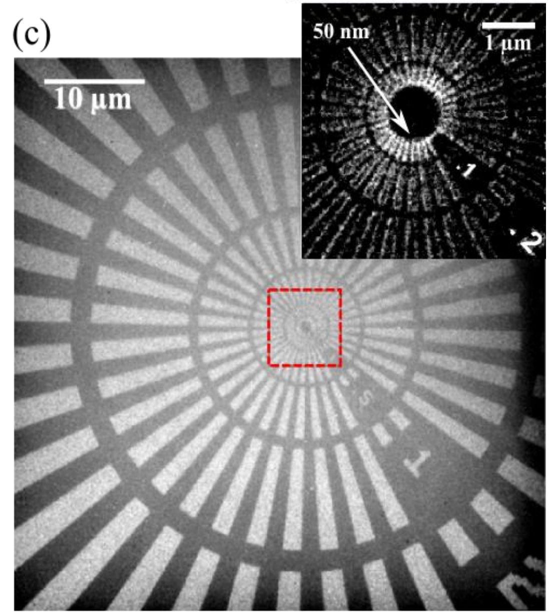
40 µJ/cm²/pulse
FOV ~ ∅100µm

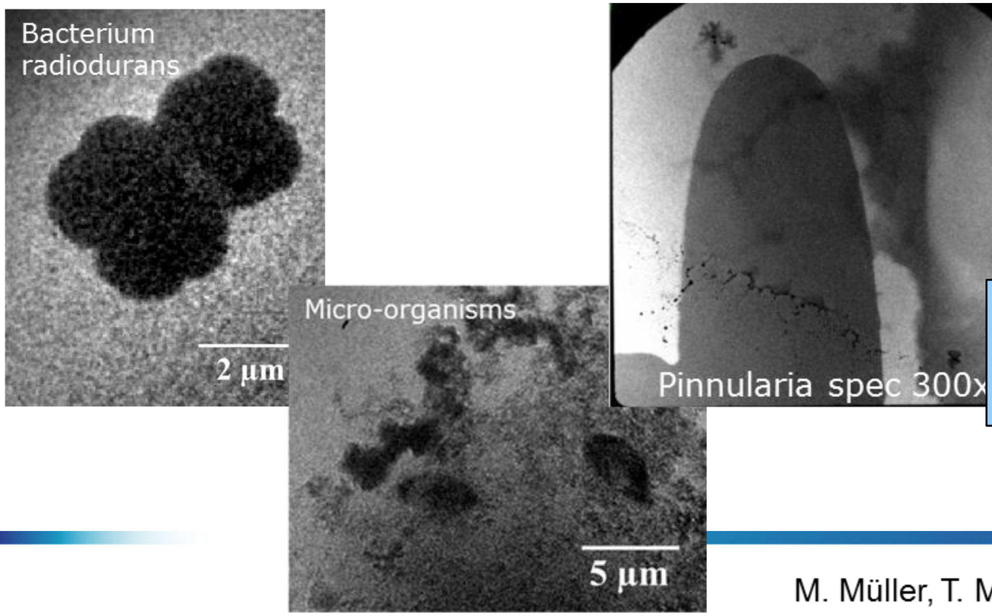
Peak brillance
~10^{17} Ph./(s mrad² mm²)

Table-top x-ray microscope @λ=2.88nm



1 m





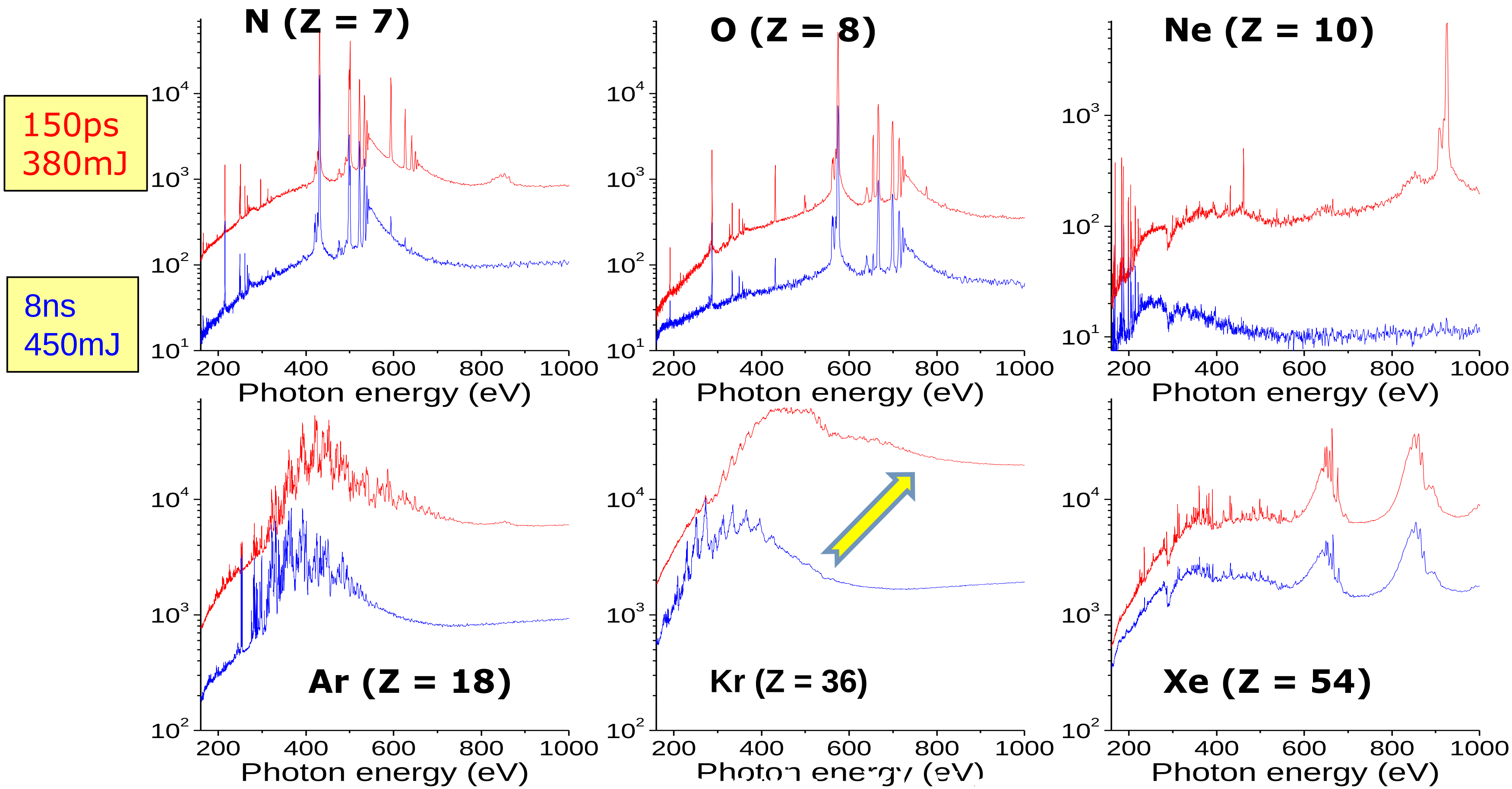
- Spatial resolution ≈ **50 nm** (up to now)
- Compact, stable soft x-ray microscope

Exposure times: ~ min…h !

M. Müller, T. Mey, J. Niemeyer, K. Mann: Optics Expr. (2014)

Brilliance improvement I: ns → ps laser

Single pulse XUV spectra



Peak brillance of isolated N line @ λ = 2.88nm:

M. Müller, K. Mann et al.: Optics Exp. **21** (2013)

$6*10^{17}$ (ns-Laser) $\Rightarrow$ $1.2*10^{20}$ Ph./(s mrad^2 mm^2 0,1%BW) (ps-Laser)

Brilliance improvement II:
High Average Laser Power

Laser-
Laboratorium
Göttingen e.V.

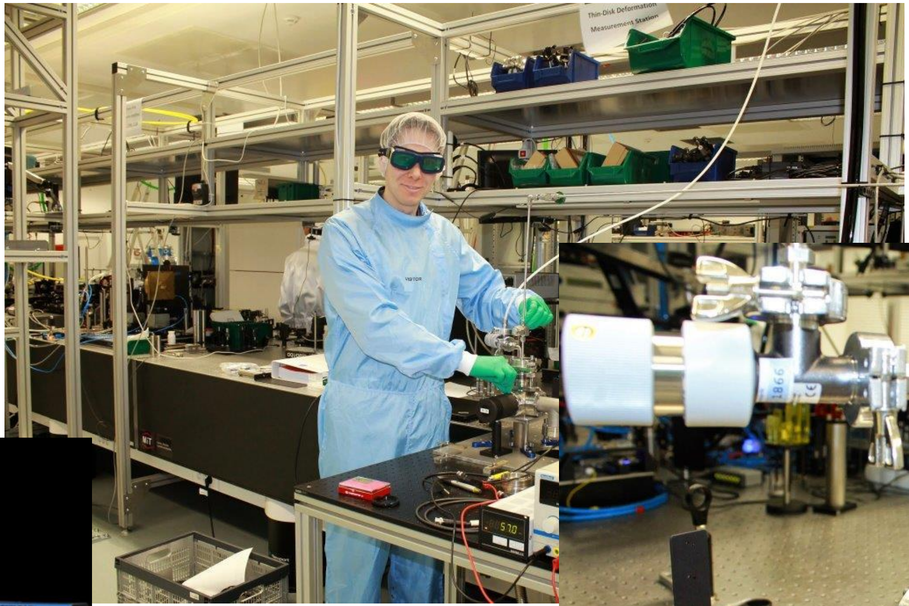
Hilase Beamline B

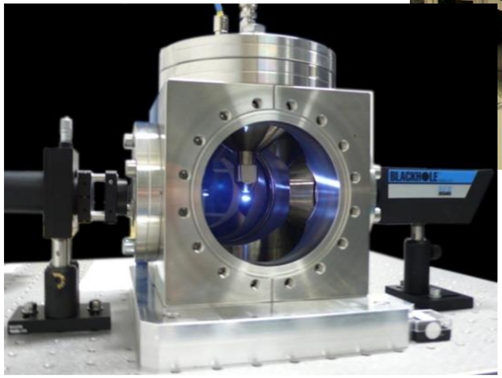
τ ~ ns, P< 5W → **τ ~ ps, P=500W, 1kHz**

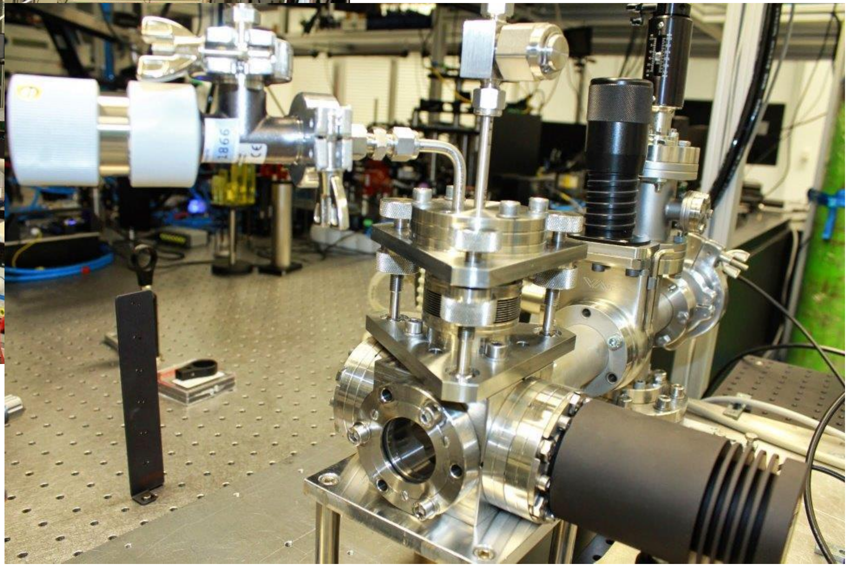
hilase

T. Mocek, A. Endo

Test Setup:

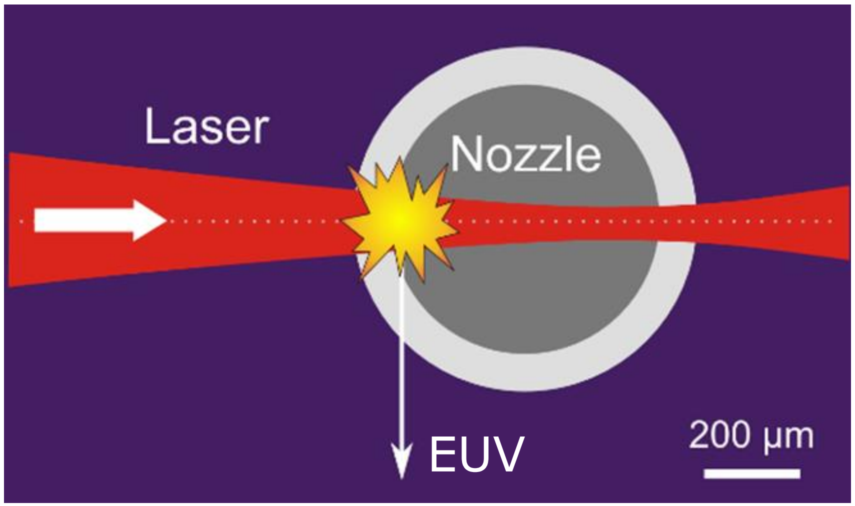


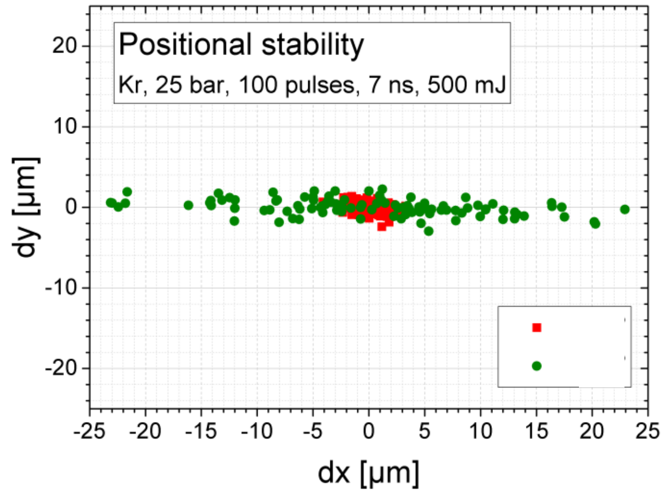




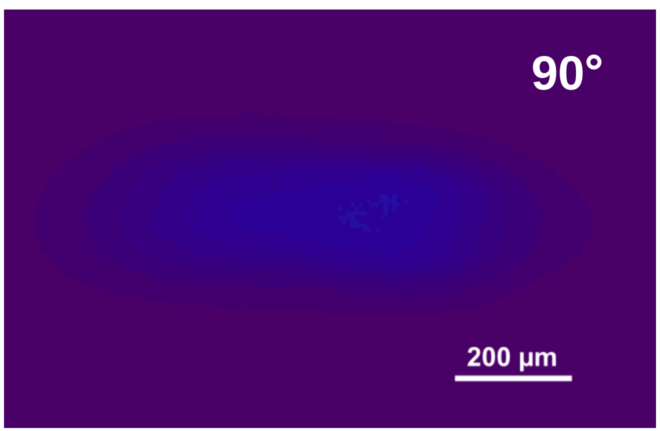
Brilliance improvement III: Anisotropy of plasma emission

Laser-Laboratorium Göttingen e.V.





Krypton 25 bar, 7 ns, 500 mJ



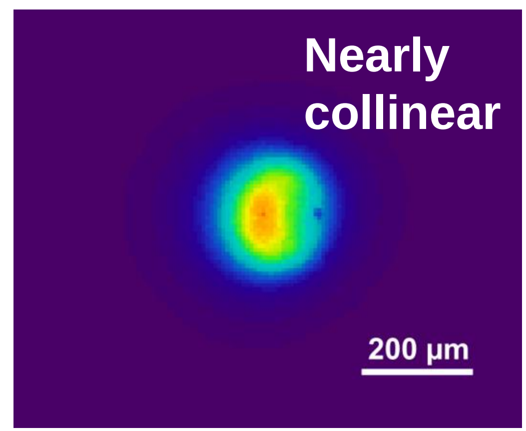
610 µm x 205 µm (FWHM)

Maximum: x 6.5

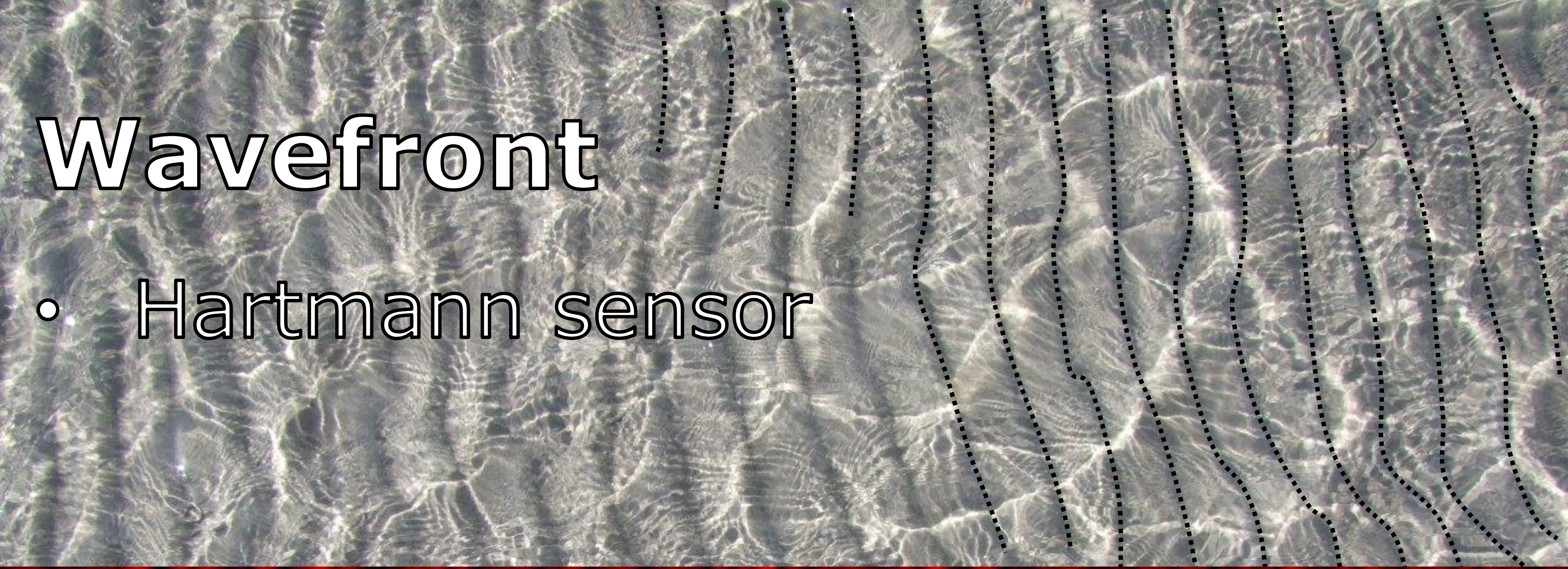
Total Energy: x 1.5

Area: x 0.2

Brillance increase: x 7…10



140 µm x 190 µm (FWHM)



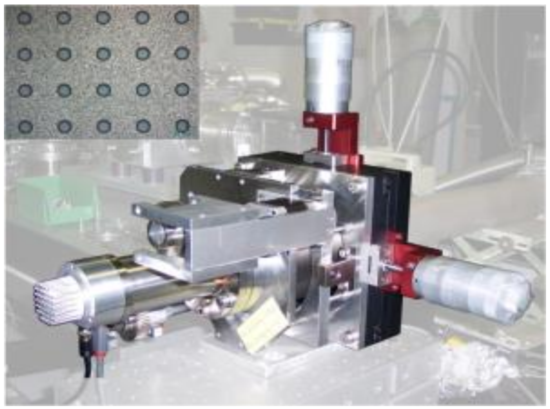
Wavefront

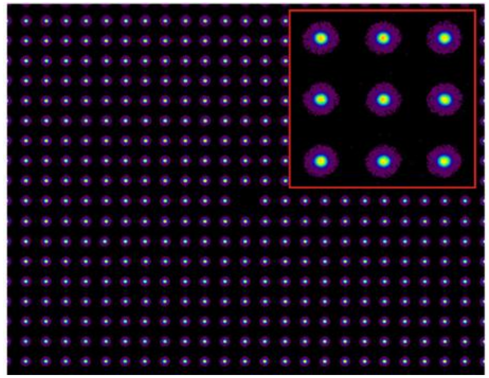
- Hartmann sensor

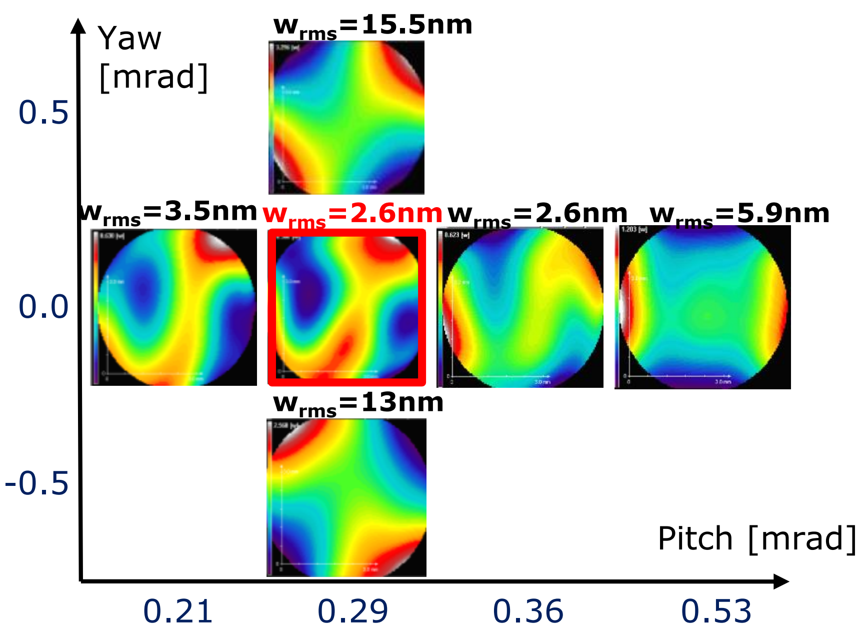
Spatial Coherence

- Wigner formalism

Wavefront measurement at FEL @λ=13,5nm: On-line adjustment of optics



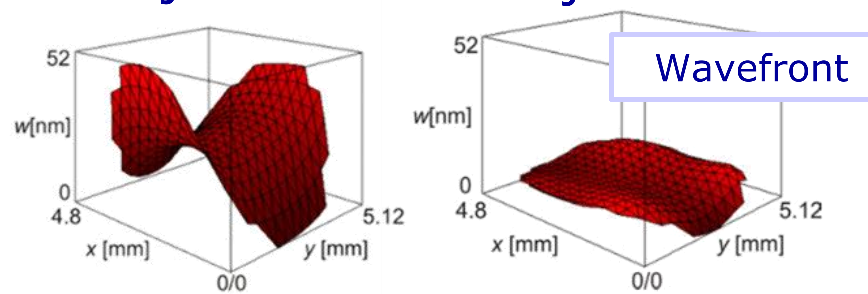




B. Flöter , K. Mann, K. Tiedke et al., Nucl. Instrum. Meth. (2011)

before adjustment

after adjustment



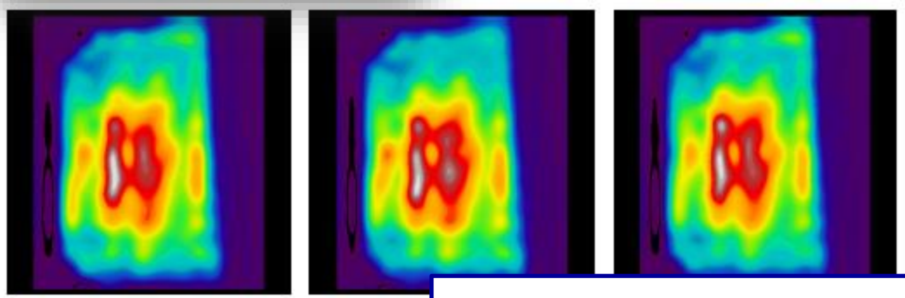
w_{rms}~ 10nm

w_{rms}~ 2.5nm ~ λ/10

EUV wavefront measurements

Laser-
Laboratorium
Göttingen e.V.

LCLS

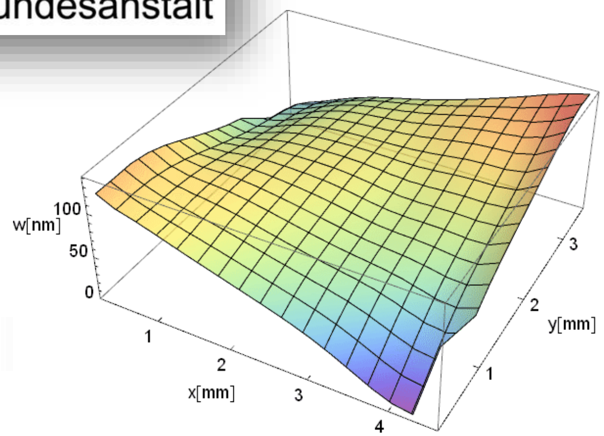


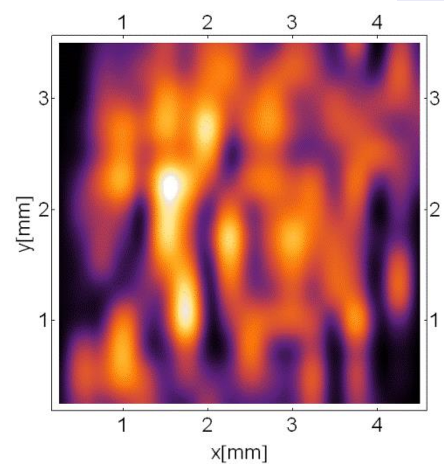
High pulse-to-pulse stability!

FERMI @elettra

Adjustment of active KB-system
→ 10µm x 10µm focal size

PTB Physikalisch Technische Bundesanstalt



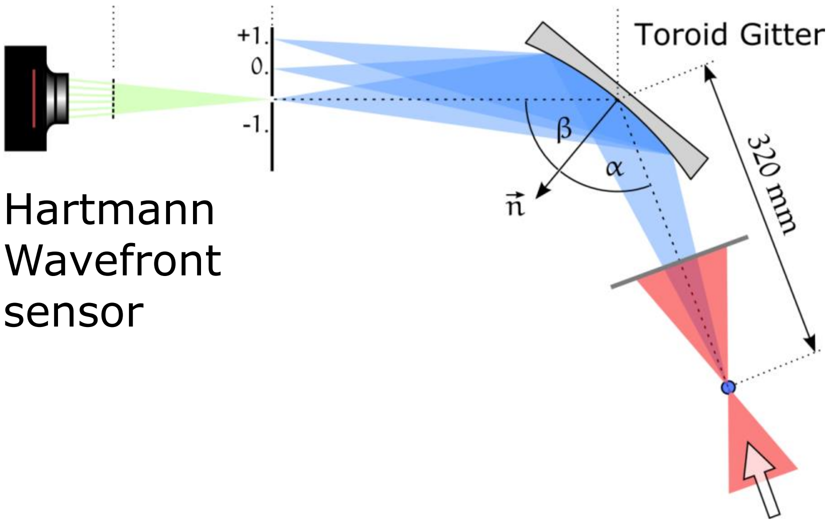


Online optics alignment
at MLS synchrotron
at 13.5 nm

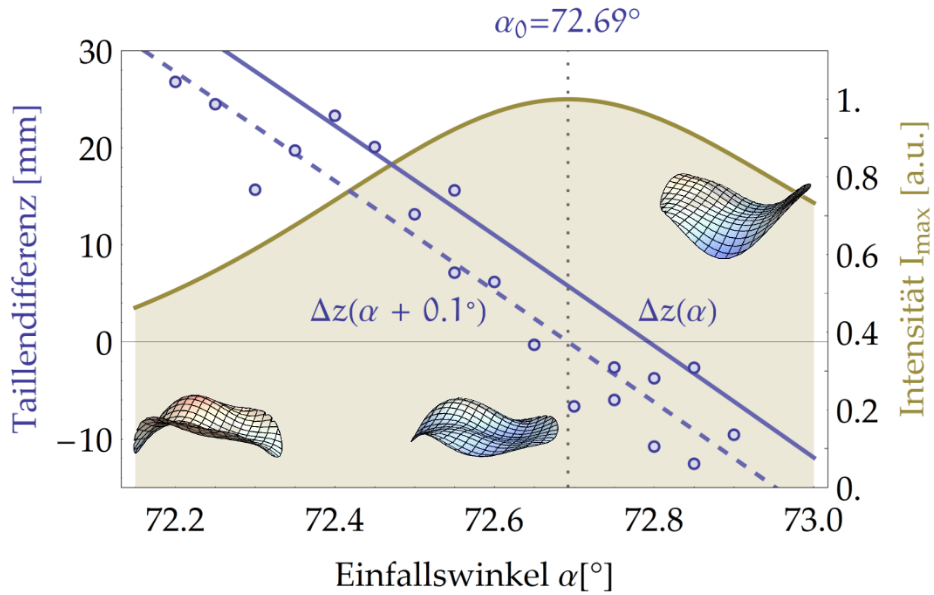
Optimization of HHG beam transport

by EUV Hartmann wavefront sensor

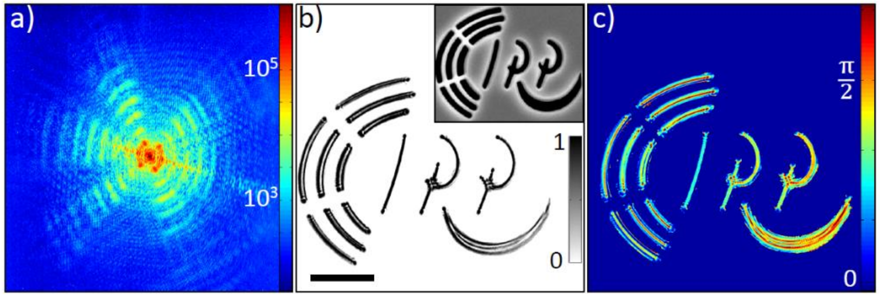
25th harmonic (λ = 32nm)



Hartmann Wavefront sensor



Coherent Diffractive Imaging

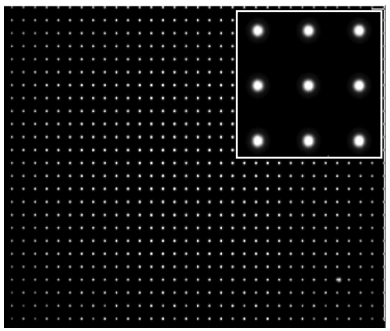


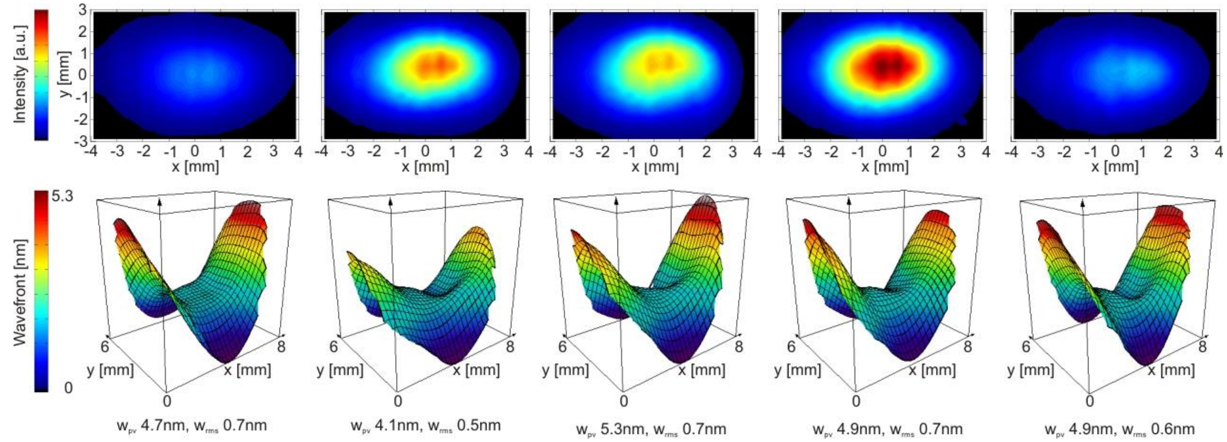
T. Mey, S. Zayko, K. Mann, C. Ropers: Optics alignment of single high-harmonics by EUV Hartmann sensor, Opt. Express (2015)

S. Zayko, M. Sivis, C. Ropers et al, Opt. Express (2015)

Beam parameters from Hartmann data FLASH BL2 @λ=7nm

Beam profiles and wavefronts of single pulses:





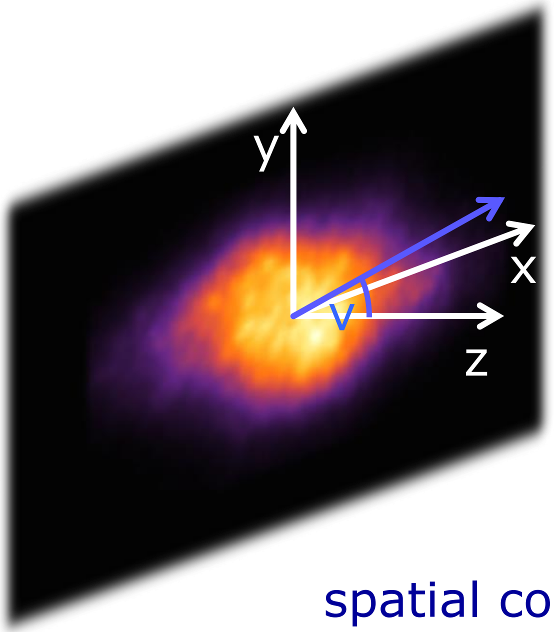
Beam parameters	***X***	***Y***
w_{pv} [nm]	5.3 ± 0.69	
w_{rms} [nm]	0.67 ± 0.09	
Beam propagation parameter M^2	1.15 ± 0.08	
Beam propagation parameter M^2_i	1.23 ± 0.1	1.1 ± 0.1
Beam width d [mm]	6 ± 0.2	4.4 ± 0.1
Waist position $z_{0,i}$ [m]	-109.2 ± 0.9	-99.2 ± 1.4
Rayleigh length z_R [mm]	3760 ± 484	5090 ± 731
Waist diameter $d_{0,i}$ [µm] 2nd moment	200 ± 20	223 ± 25
Divergence θ[µrad]	55 ± 2	44 ± 2

Evaluation of:
- Intensity profile / Beam size
- Pointing stability
- Wavefront / Zernike coefficients
- Waist position and size
- Beam divergence
- Beam parameter product M^2

No information on coherence !

Wigner distribution

Laser-
Laboratorium
Göttingen e.V.



h = Fourier transform of Mutual Coherence Function:

Wigner distribution

mutual coherence functi

$$h(\vec{x},\vec{u}) = \left(\frac{1}{2\pi}\right)^2 \cdot \iint \Gamma(\vec{x},\vec{s}) \cdot e^{-i\vec{u}\cdot\vec{s}} d^2 s$$

spatial coordinate $\vec{x} = \binom{x}{y}$ angular coordinate $\vec{u} = \binom{u}{v}$

Irradiance

$$I(\vec{x}) = \iint h(\vec{x},\vec{u}) du dv$$

$\rightarrow$ Near field

Wavefront

$$\nabla w = \lambda^2 \int \vec{u} \cdot h(\vec{x},\vec{u}) d\vec{u}$$

Global degree of coherence

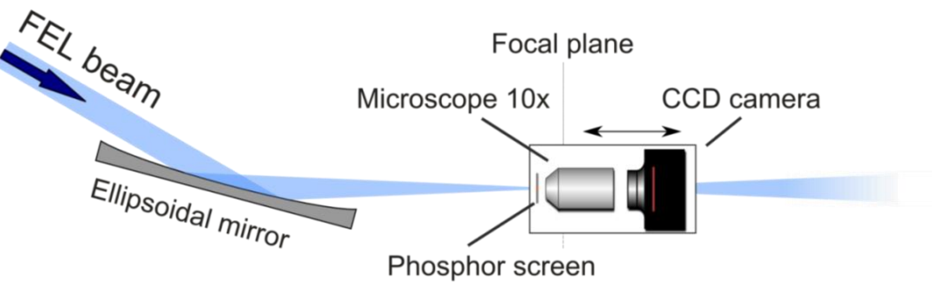
$$\mathrm{K} = \lambda^2 \frac{\iint h(\vec{x},\vec{u})^2 dx^2 du^2}{\iint h(\vec{x},\vec{u}) dx^2 du^2}$$

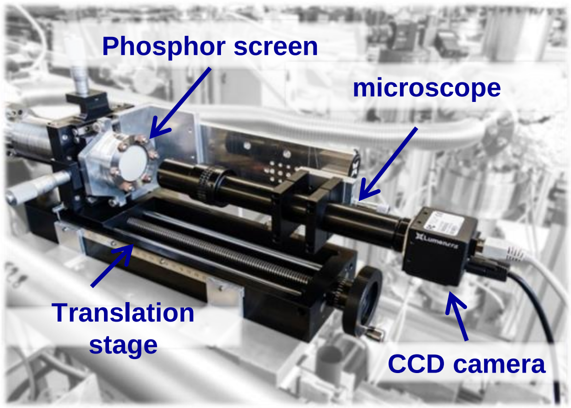
M. J. Bastiaans, 1986, *Opt. Acta* **28** 1215-24

Determination of Wigner distribution for FEL @λ=13.5nm

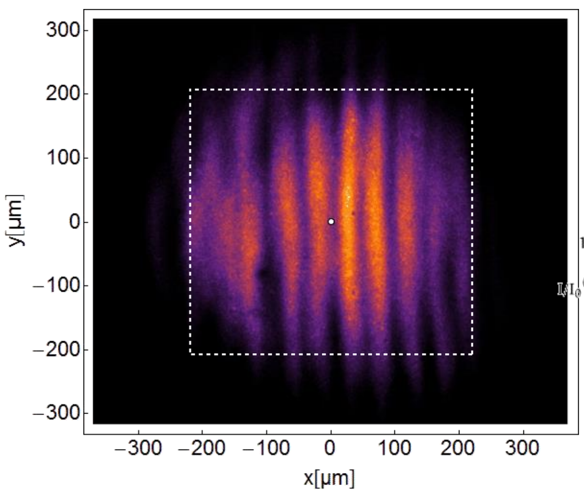
Laser-Laboratorium Göttingen e.V.

Caustic of FLASH:



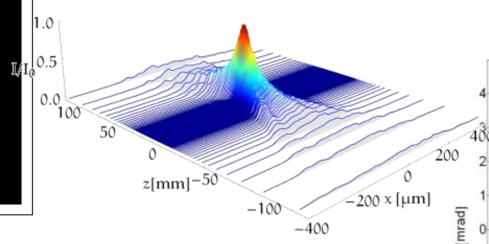


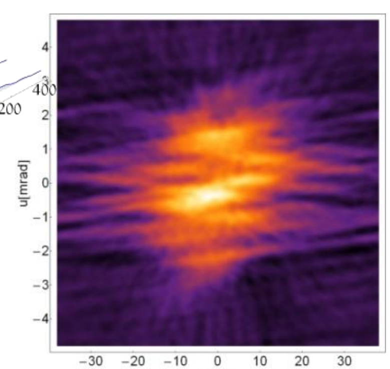
Intensity distribution



"tomographical" mapping data into 4D Wigner Fourier space

Wigner function
= Fourier transform of **Mutual Coherence Function**





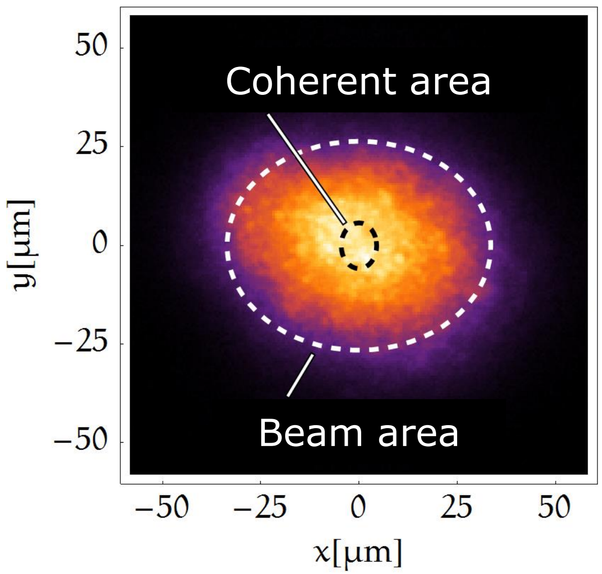
⇒ **comprehensive beam characterization**

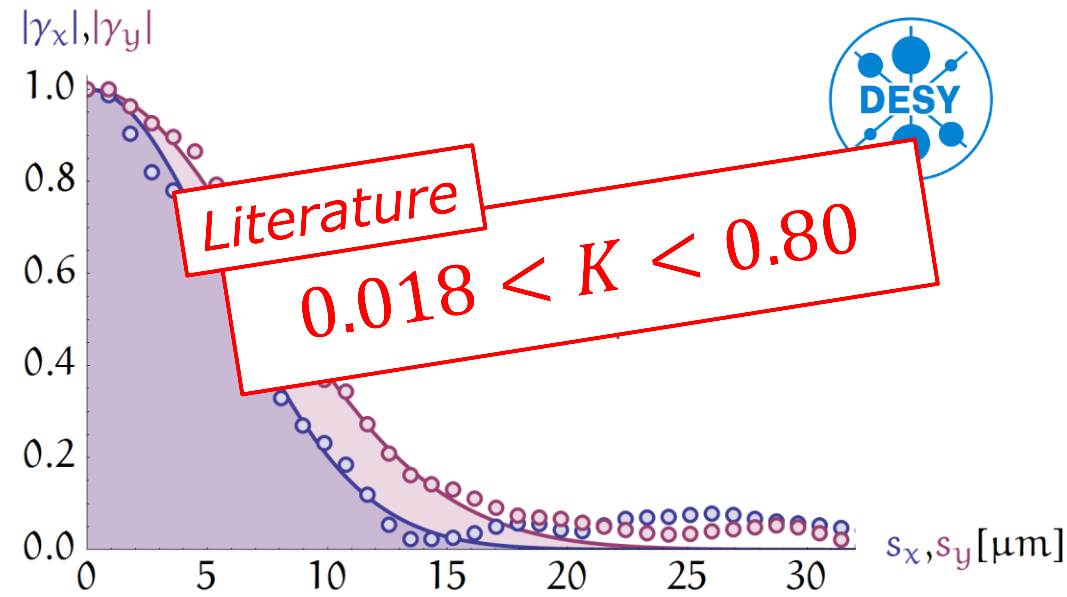
- *beam parameters*
- *angular characteristics*
- *spatial coherence*
- *wavefront*

T. Mey, B. Schäfer, K. Mann, K. Tiedtke et al., Optics Express 2014

Coherence properties of FLASH

Laser-Laboratorium Göttingen e.V.





	Wavelength λ [nm]	Beam diameter d_x / d_y [μm]	Coherence length l_x / l_y [μm]	Global degree of coherence K
Wigner [2]	24.7	67 / 53	5.5 / 7.2	0.032
Double pinhole [1]	8.0	17 / 17	6.2 / 8.7	0.42

[1] A. Singer *et al.*, "Spatial and temporal coherence properties of single free-electron laser pulses," Opt. Expr. **20**, 17480-17495 (2012)
[2] T. Mey *et al.*, "Wigner distribution measurements of the spatial coherence properties of the free-electron laser FLASH," Opt. Expr. **22**, 16571-16584 (2014)

Summary:

Laser-
Laboratorium
Göttingen e.V.

- **Laser plasma based EUV / soft x-ray source**
  - Compact, clean, long-term stable
  - EUV metrology
  - NEXAFS
  - soft x-ray microscopy
- **Hartmann wavefront sensor**
  - Alignment of optics
  - Beam characterization (EUV – x-rays)
- **Wigner distribution**
  - Comprehensive description of partially coherent beams

Thank You !

Laser-
Laboratorium
Göttingen e.V.

Coworkers:

- *Dr. B. Schäfer*
- *Dr. U. Leinhos*
- *Dr. T. Mey*
- *M. Müller*
- *M. Stubenvoll*
- *M. Schellhorn*
- *J. Holburg*
- *J.O. Dette*
- *M. Lübbecke*

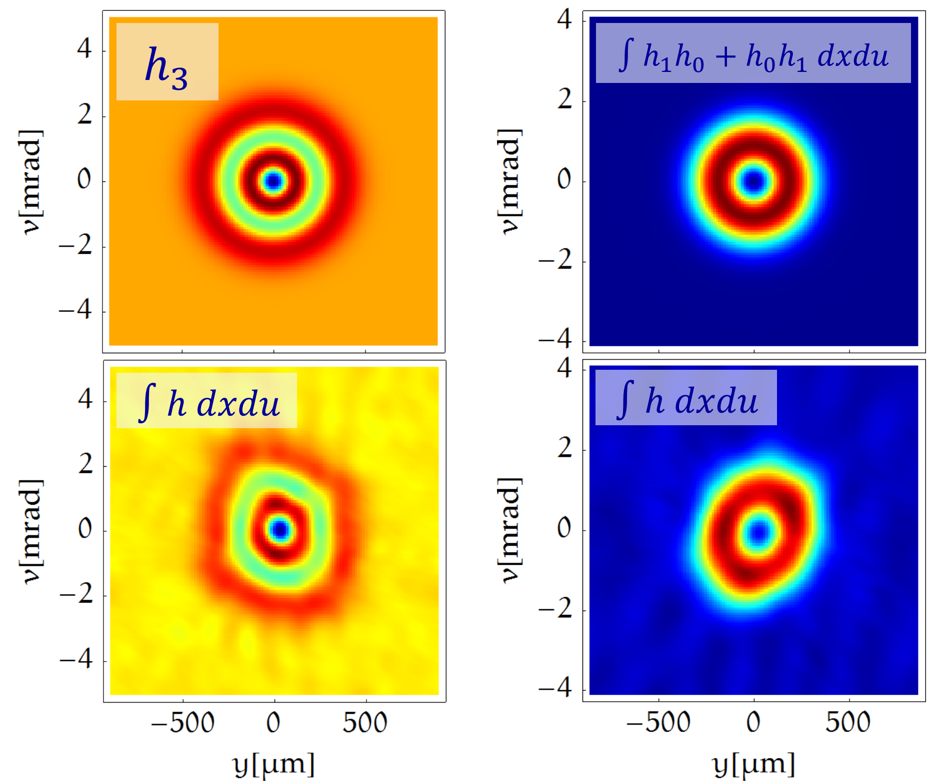
BMBF project
„WeKokUbS"

SFB 755
Nanoscale Photonic
Imaging

4D - Wigner distribution

Global degree of coherence K

	Theory	Experiment
TEM$_{00}$	1	0.95
TEM$_{10}$	1	1.06
TEM$_{02}$	1	0.98
TEM$_{03}$	1	0.90
TEM$_{01}$ +TEM$_{10}$	0.5	0.46



T. Mey, "Measurement of the Wigner distribution function of non-separable laser beams employing a toroidal mirror," New J. Phys. **16**, 123042 (2014)